Semi-Annual Progress Report No. 4

NASA Grant NsG-588

Theoretical and Experimental Studies of
Radiation-Induced Damage to Semiconductor
Surfaces and the Effects of this Damage on
Semiconductor Device Performance

1 September 1965 through 28 February 1966

Prepared by

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- FORWARD -

This report contains a comprehensive review of research activities of the North Carolina State University's Semiconductor Device Laboratory under the sponsorship of NASA grant NsG-588.

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PUBLICATIONS AND REPORTS
(1 September 1965 through 28 February 1966)

M. A. Littlejohn and R. W. Lade, Silicon surface damage due to gamma radiation, Proc. Nat'l. Electronics Conf., 21, pp. 67-72; Oct., 1965.

R. J. Mattauch and R. W. Lade, Surface state density variations on MOS structures due to gamma radiation, Proc. IEEE, 53, p. 1748; Nov., 1965.

CONTENTS

PROJECT NO. 588-1. SURFACE RECOMBINATION VELOCITY INVESTIGATIONS

STAFF: M. A. LITTLEJOHN AND R. W. LADE

The object of this research is to study the effects of Co^{60} gamma irradiation (approximately 1.3 Mev) on both the bulk and surface properties of silicon. Transient methods are used to study bulk and surface recombination rates by first assuming that recombination takes place through a single energy level (recombination center) in the forbidden energy region. This implies that the Shockley-Read-Hall recombination theory applies, and using computer techniques, parameters which describe this recombination center are obtained. Thus, a meaningful enterpretation of experimental data can be made.

During the past six months, work has been completed on surface recombination velocity measurements in silicon. One paper entitled "Silicon Surface Damage Due to Gamma Radiation" has been published in volume XXI of the Proceedings of the National Electronics Conference and this paper was also orally presented at the National Electronics Conference at Chicago in October, 1965.

Several 100 ohm-cm n-type samples were sent to RCA Laboratories at Princeton, N. J. for a low temperature ($700^{\circ}C$) oxidation. An attempt to measure the lifetimes of these samples by photoconductive decay (PCD) was fruitless. The problems were exactly as described in SDL report No. 3-588 when similar oxidations were carried out at $1000^{\circ}C$. The heat treatment during oxidation reduced the lifetime by more than two orders

of magnitude and thus it becomes almost impossible to measure lifetime by PCD. The samples were then sent to NASA IRD Langley for lifetime measurements using X-ray techniques capable of measuring much smaller lifetimes. However, this technique yielded no further information. All attempts at measuring surface velocities on SiO_2 passivated surfaces by PCD have been unsuccessful in this laboratory.

Work has begun on the use of the temperature dependence of bulk and surface lifetime as a technique for investigating radiation damage. This technique is quite common in the study of bulk damage, but no evidence has been found of its use as a tool in the study of the surface. If a proper interpretation is made, this should be a very useful technique.

The instrumentation used is essentially the same as that described in SDL report No. 1-588. A Hafstrom-Thompson temperature chamber is used to control the temperature of the sample. The temperature is measured using a chromel-alumel thermocouple and a Leeds and Northrup millivolt potentiometer. Liquid CO_2 is used as a refrigerant and the lifetime can thus be easily measured over a temperature range of 200-400 degrees Kelvin. During the initial measurements the temperature range was 300-400 degrees Kelvin. Two n-type 100 ohm cm samples were prepared for measurements (Samples 1NA58-6 and 1NA$5-10). One is a bulk sample and the other a thin filament (.05 cm x 0.5 cm x 1.5 cm) for surface measurements. The surface preparation consisted of mechanically lapping the sample with 800 and 10μ lapping compound and then chemically polishing with a solution

of 90% HNO₃ and 10% HF (reagent grade acids). The bulk sample

was lapped with 120 grit to provide an infinite surface

recombination velocity ($>10^4$ cm/sec).

Figs. 1 and 2 show the temperature dependence of the bulk

and surface lifetimes of the two n-type samples. Also shown

is a plot of the theoretical Shockley-Read-Hall model which

gives a best fit to the data over the temperature range 300-400

degrees Kelvin. It should be noted that both experimental

curves exhibit a maximum value for temperatures near 430-440°K

while the theoretical curves do not. This maximum is predicted

by the Shockley-Read-Hall model [1] while the theoretical

equation is invalid for temperatures greater than approximately

400°K.

Before any irradiations could be carried out, the effects

of annealing had to be investigated so that when examining the

temperature dependence of lifetime any annealing of damage could

be avoided. Five previously irradiated bulk samples (total

dosage $\approx$ 1.0 x 10⁶ roentgens) were annealed at various temper-

atures for approximately 15 min. and then slowly cooled back to

room temperature. The lifetimes were measured as an indication

of annealing. Fig. 3 shows the results of these experiments

and from these results it is deduced that annealing occurs at

a threshold temperature for this gamma dosage of near 410.0°K.

The samples were irradiated in an argon atmosphere, and

the results of these irradiations are indicated in Figs. 4 - 11

Before discussing these experimental results, the theoret-

ical implications of the well-known Shockley-Read-Hall model

FIGURE 1

BULK LIFETIME
VS TEMPERATURE
SAMPLE 1NA58-6
PRE-IRRADIATION
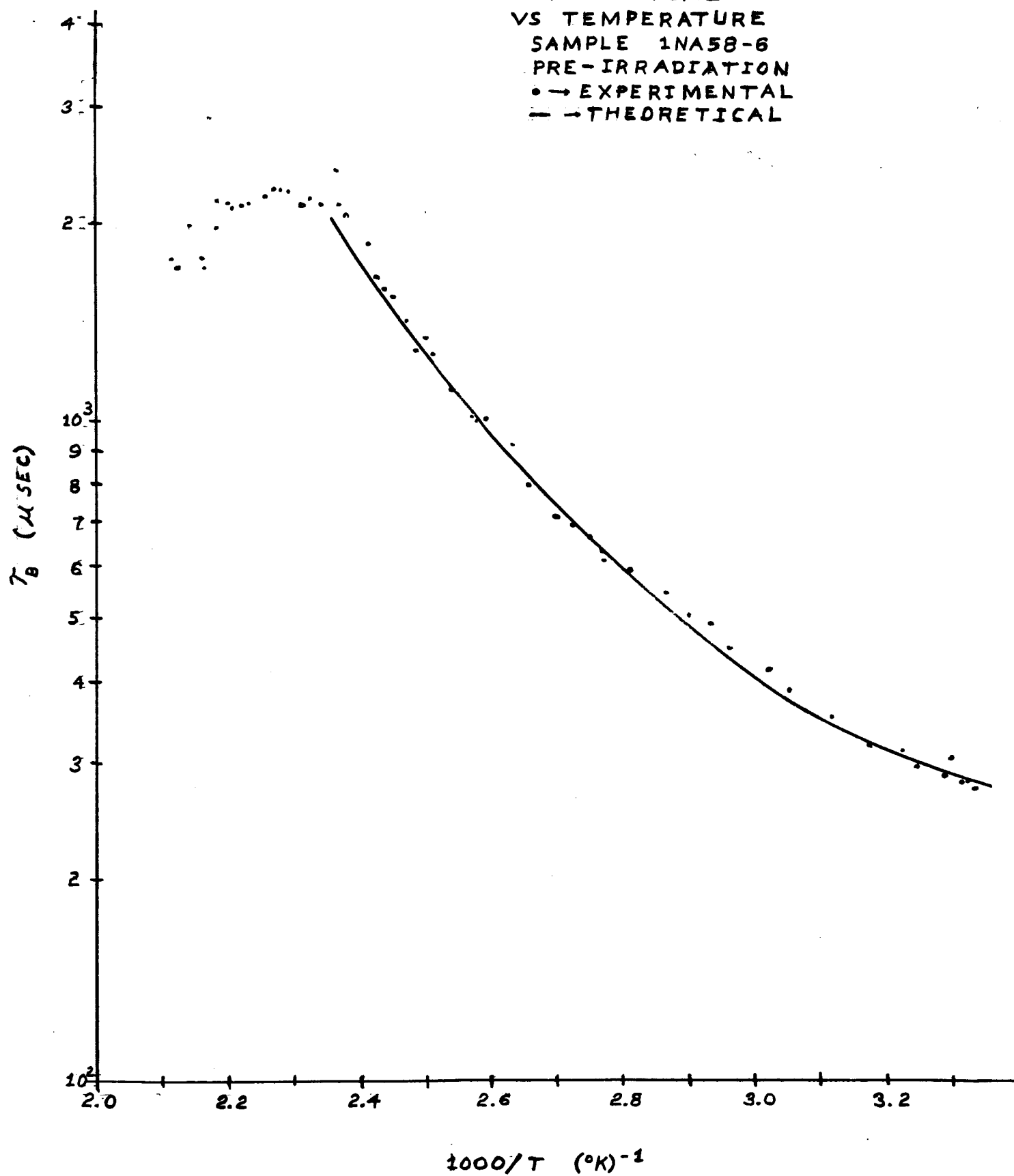• → EXPERIMENTAL
— → THEORETICAL

FIGURE 2

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SURFACE LIFETIME
VS TEMPERATURE
SAMPLE 1NA½5-10
PRE - IRRADIATION
o → EXPERIMENTAL
— →THEORETICAL
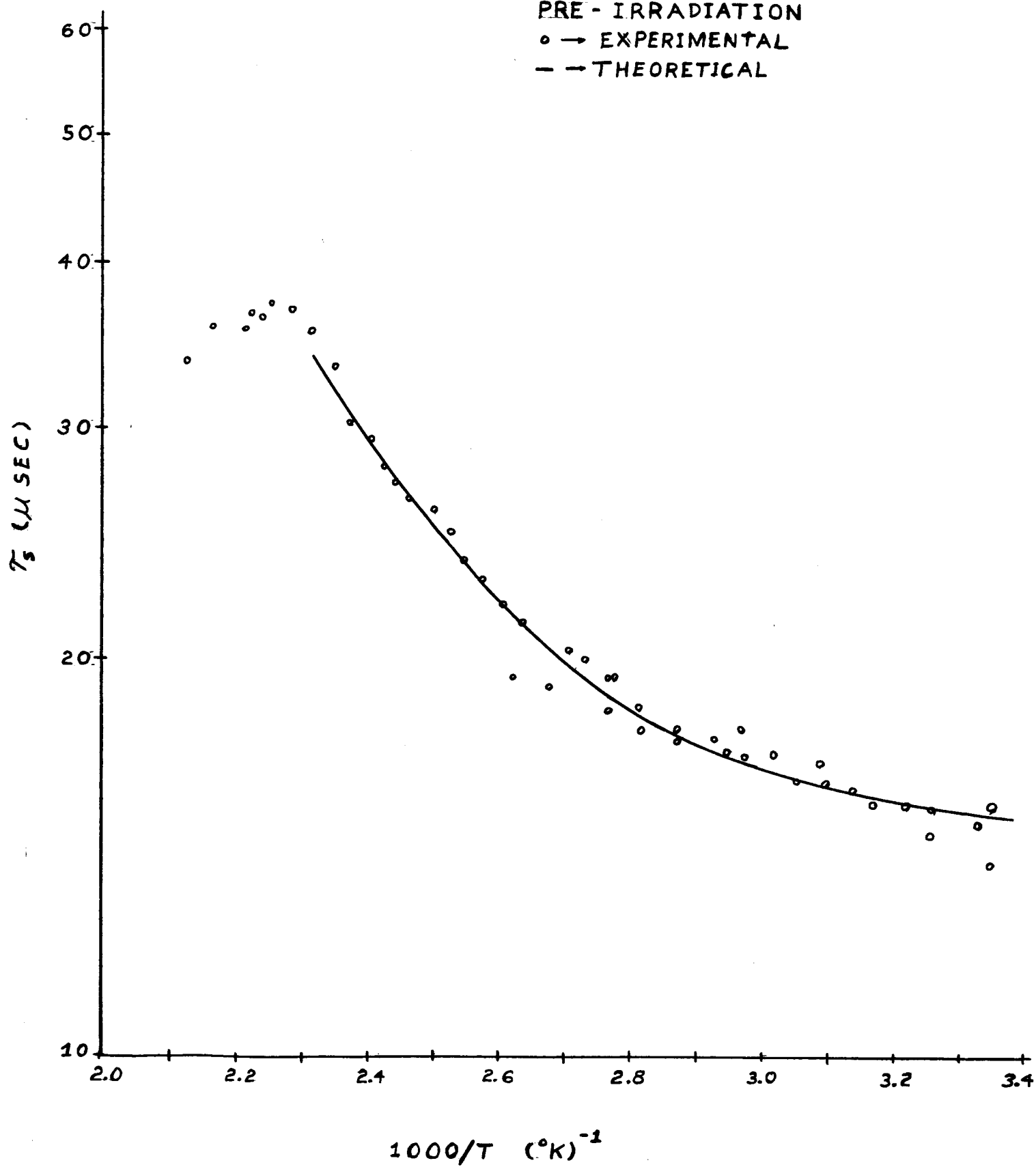
FIGURE 3
ANNEALING TIME APPROX. 5-15 MIN.

FIGURE 4

BULK LIFETIME
VS TEMPERATURE
SAMPLE 1NA58-6
AFTER 5.1 × 10⁴ ROENTGENS
OF CO⁶⁰ GAMMA RADIATION
• → EXPERIMENTAL
— → THEORETICAL
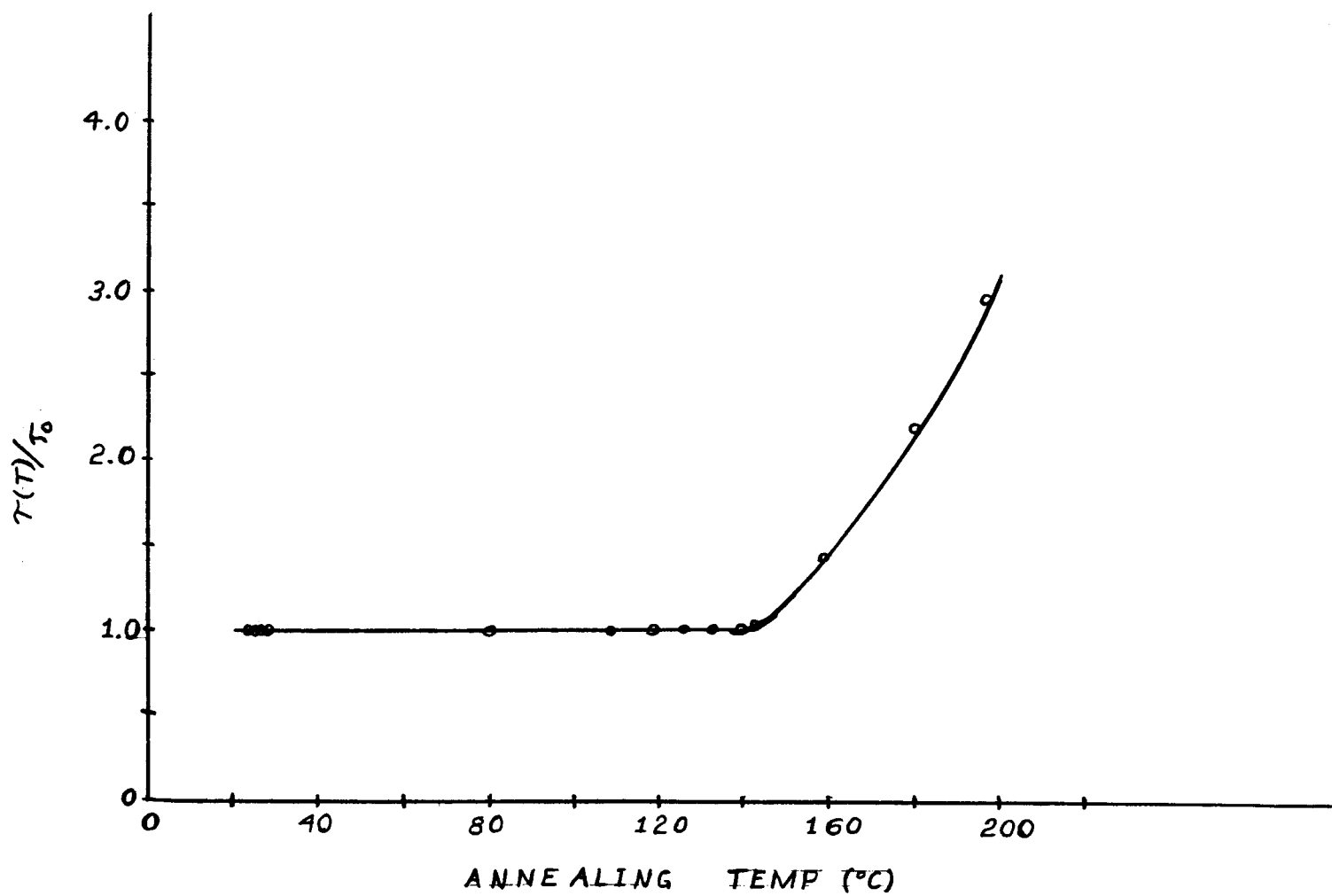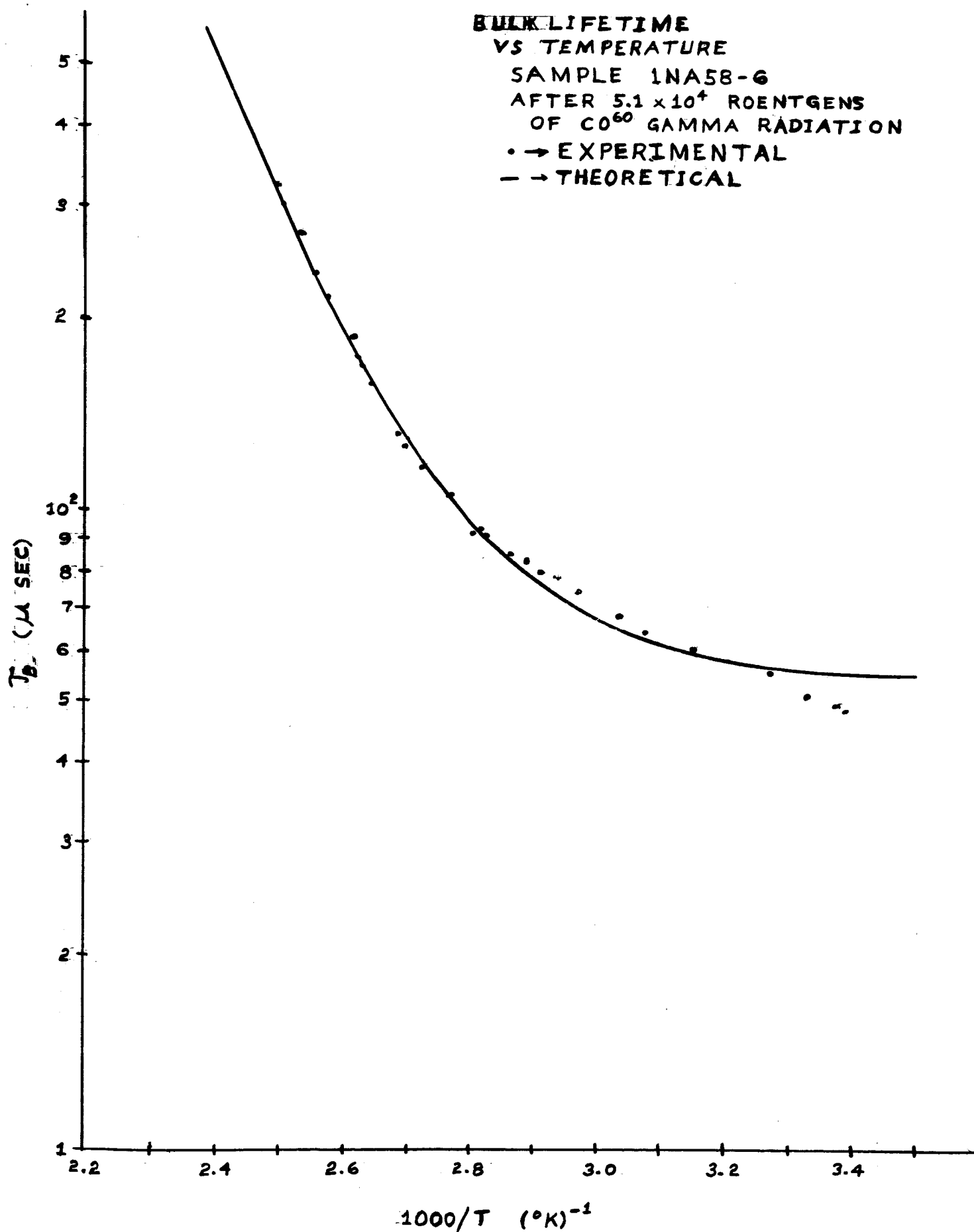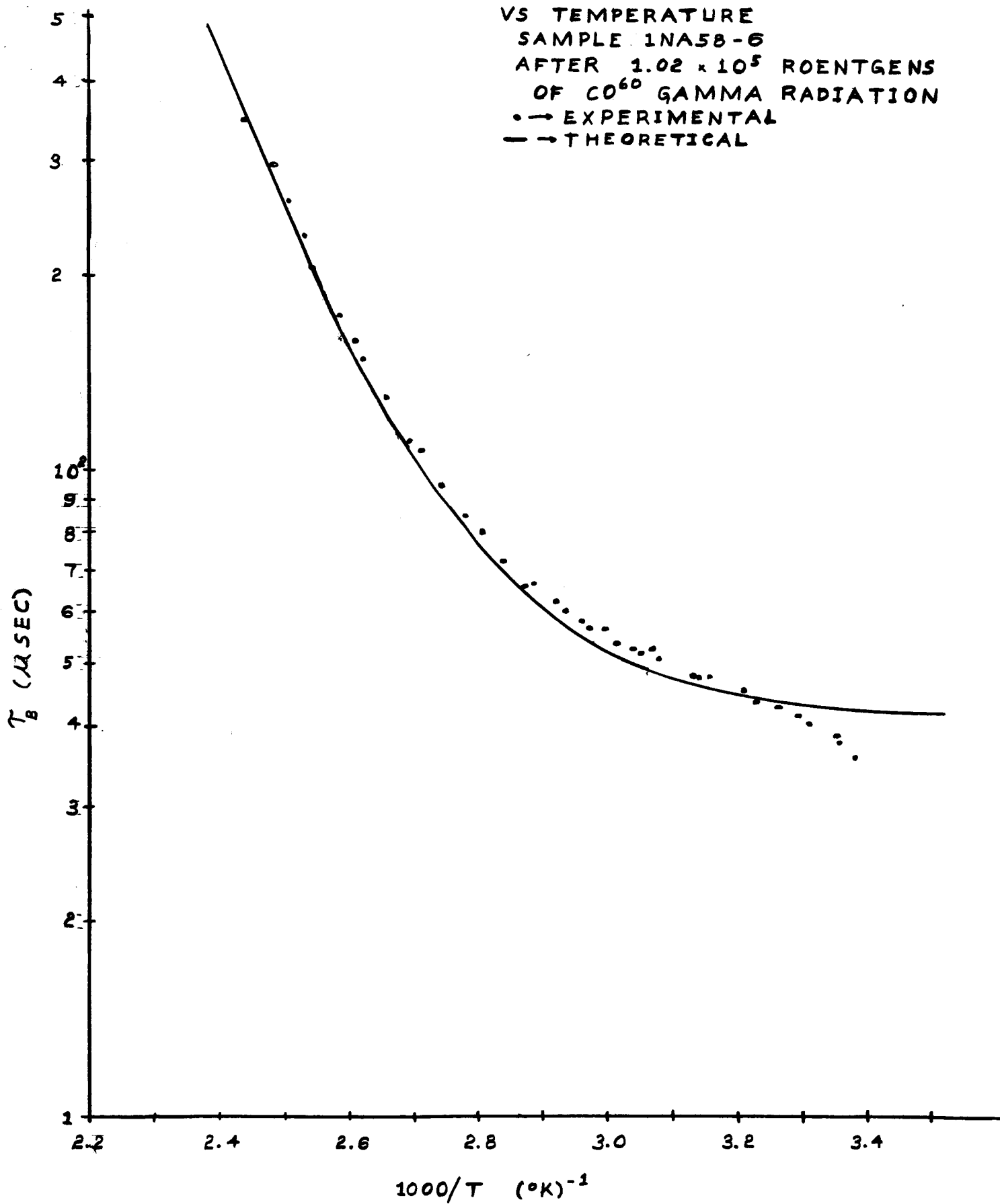
FIGURE 5   8

BULK LIFETIME
VS TEMPERATURE
SAMPLE 1NA58-6
AFTER 1.02 x 10^5 ROENTGENS
OF CO^{60} GAMMA RADIATION
•→ EXPERIMENTAL
—→ THEORETICAL

$1000/T \ (°K)^{-1}$

FIGURE 6

9

BULK LIFETIME
VS TEMPERATURE
SAMPLE 1NA58-6
AFTER 2.03 x 10⁵ ROENTGENS
OF CO⁶⁰ GAMMA RADIATION
• →EXPERIMENTAL
— →THEORETICAL

τ_B (μ SEC)

$1000/T$ (°K)$^{-1}$
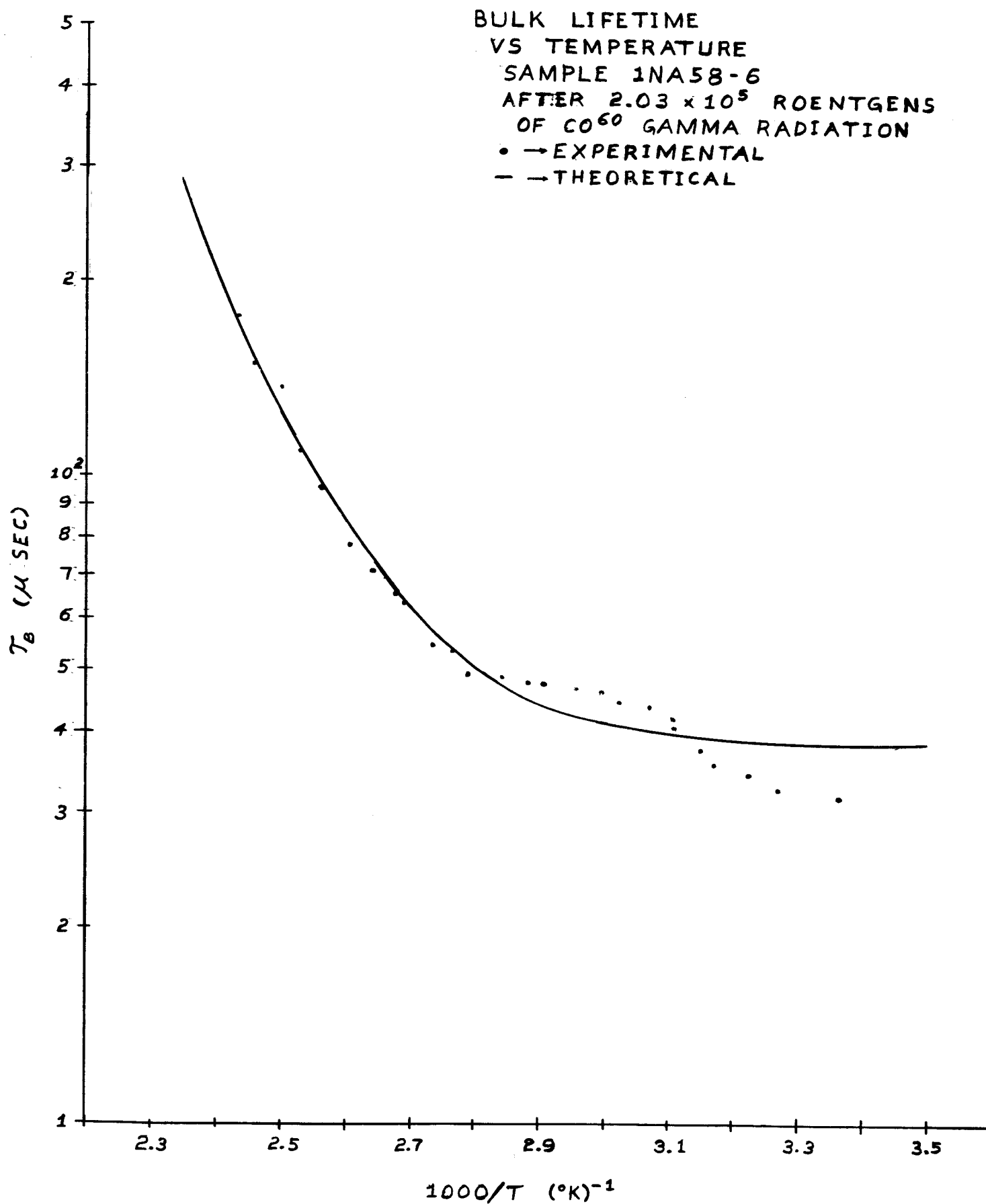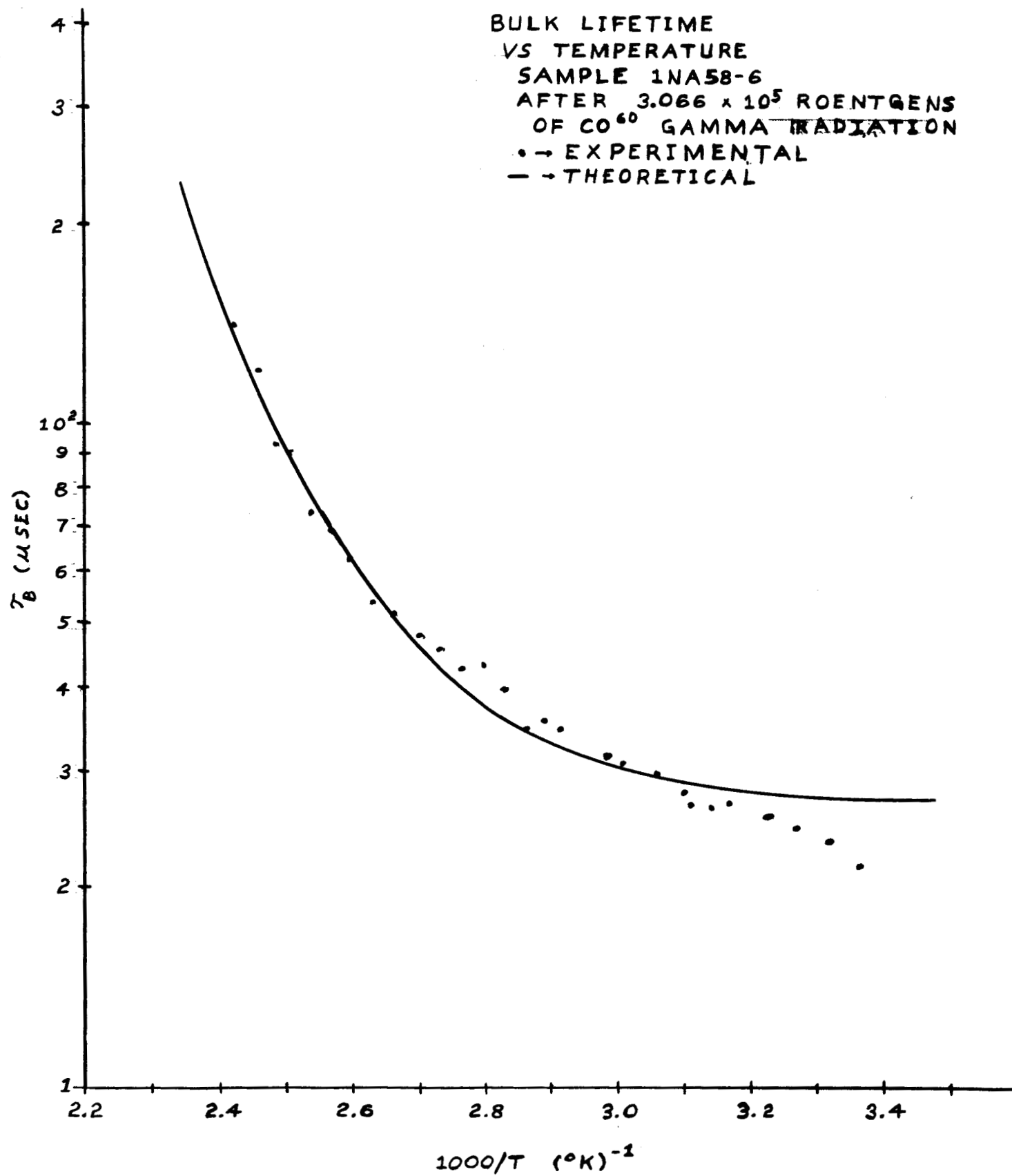
FIGURE 7

10

BULK LIFETIME
VS TEMPERATURE
SAMPLE 1NA58-6
AFTER 3.066 x 10⁵ ROENTGENS
OF CO⁶⁰ GAMMA IRADIATION
• → EXPERIMENTAL
— → THEORETICAL

FIGURE 8

11

SURFACE LIFETIME
VS TEMPERATURE
SAMPLE 1NA$\frac{1}{2}$5 -10
AFTER 1.02 x 10^5 ROENTGENS
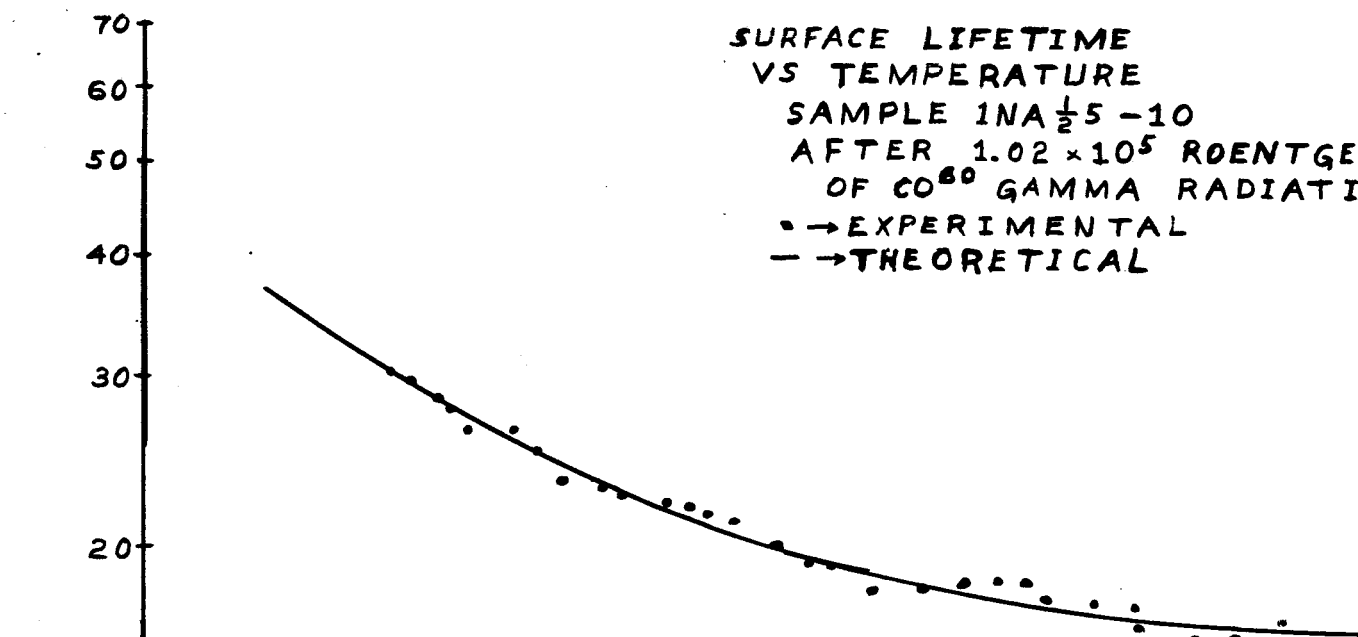OF CO^{60} GAMMA RADIATION
• →EXPERIMENTAL
— →THEORETICAL

FIGURE 9: SURFACE LIFETIME
VS TEMPERATURE
SAMPLE 1NA$\frac{1}{2}$5 -10
AFTER 5.1 x 10^4 ROENTGENS
OF CO^{60} GAMMA RADIATION
• →EXPERIMENTAL
— →THEORETICAL

τ_S (μ SEC)

1000/T (°K)

FIGURE 10   12

SURFACE LIFETIME
VS TEMPERATURE
SAMPLE 1NA½5-10
AFTER 3.066 X10⁵ ROENTGENS
OF CO⁶⁰ GAMMA RADIATION
•→ EXPERIMENTAL
— →THEORETICAL

FIGURE 11

SURFACE LIFETIME
VS TEMPERATURE
SAMPLE 1NA½5-10
AFTER ?.?? x 10⁵ ROENTGENS
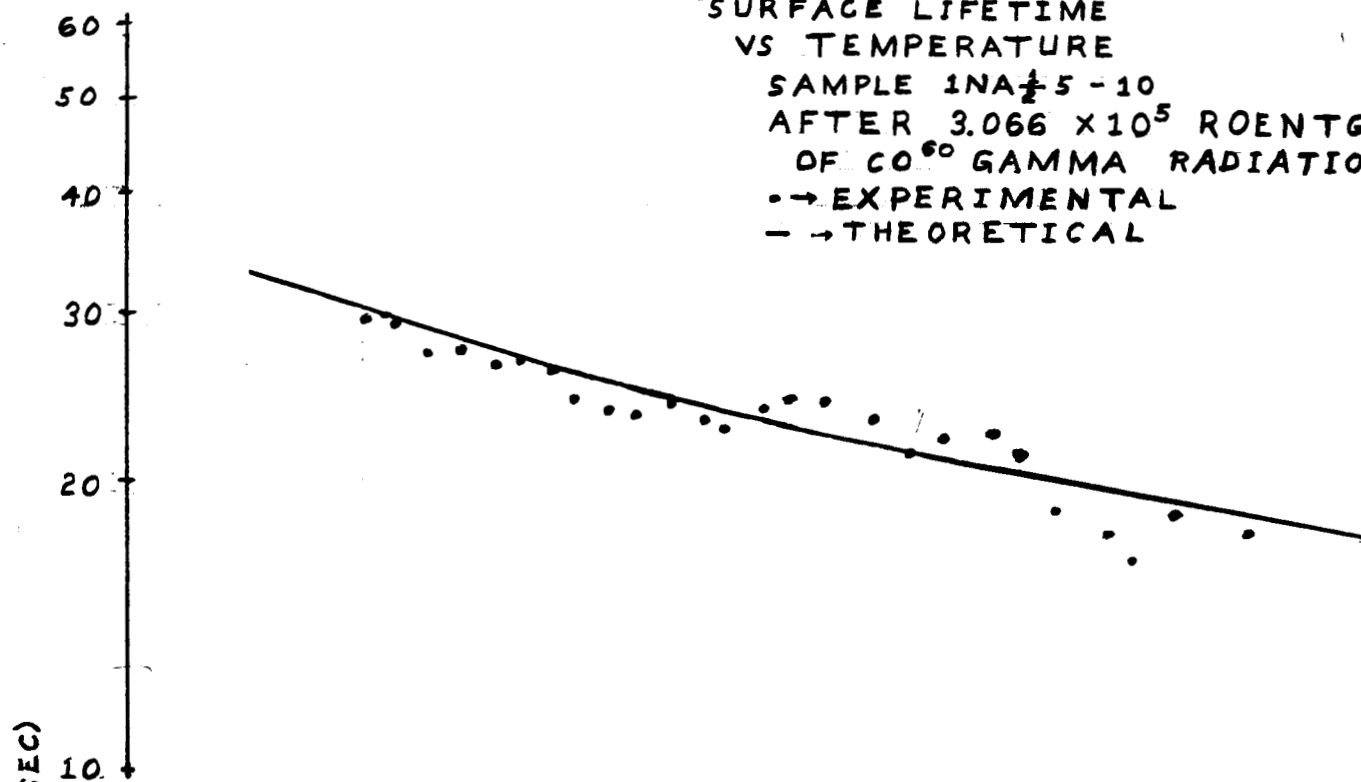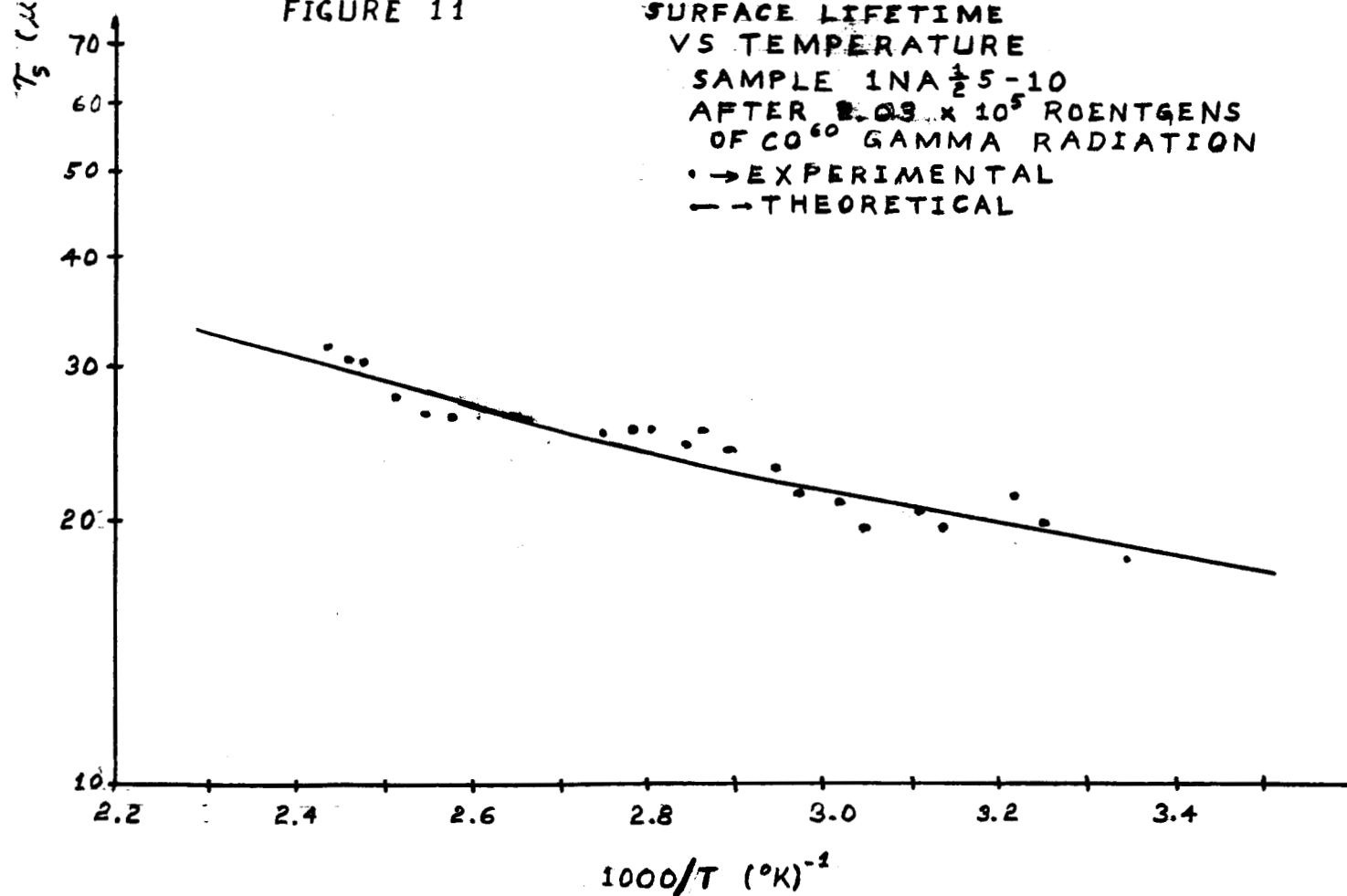OF CO⁶⁰ GAMMA RADIATION
•→EXPERIMENTAL
—→THEORETICAL

τ_s (μ SEC)

1000/T (°K)⁻¹

will be discussed. The lifetime of free carriers in a semi-conductor with a single energy level in the forbidden gap (for $\bar{n} \ll n_0$ or $\bar{p} \ll p_0$) is given by [2]

$$\mathcal{T} = \mathcal{T}_{po}\left(\frac{n_0 + n_1}{n_0 + p_0}\right) + \mathcal{T}_{no}\left(\frac{p_0 + p_1}{n_0 + p_0}\right) \tag{1}$$

where n_1 and p_1 are the densities of electrons and holes in the conduction and valence bands when the Fermi energy corresponds to the energy of the recombination center in the forbidden region. Also, $\mathcal{T}_{po}$ and $\mathcal{T}_{no}$ are the lifetimes in extrinsic n and p type material, respectively. In general, the temperature dependence of $\mathcal{T}$ is complex. However, in the temperature range $200\text{-}400^\circ K$ one can assume for n-type material that $n_0 = N_d$, the net donor density, and that $n_0 \gg p_0$. The lifetime can then be reduced to the form

$$\mathcal{T} = A + BT^{3/2}e^{-C/T} + DT^{1/2}e^{\frac{C-\alpha}{T}} + BDT^3 \tag{2}$$

Where A, B, C, and D are constant with respect to temperature and $\alpha = kE_{go}$. Here k is Boltzmann's constant and E_{go} is the width of the energy gap at $T = 0^\circ K$. Thus, the problem is to best-fit the experimental data to a curve of this type, thus determining the value of the constants.

The problem can be further simplified if other assumptions are made. Thus, for n-type material with a recombination center in the upper half of the gap, $n_0 \gg p_0$, p_1. Then

$$\tau = \tau_{po}\left(1 + \frac{n_1}{n_0}\right)$$

which has a temperature dependence of the form

$$\tau = A + BT^{3/2}e^{-C/T} \tag{3}$$

Similarly, for n-type material with the recombination center in the lower half of the gap $n_0 \gg p_0$ and $p_1 \gg n_1$, p_0. Then

$$\tau = \tau_{po} + \tau_{no}\frac{p_1}{n_0} \tag{4}$$

Which again has a temperature dependence of the form

$$\tau = A + BT^{3/2}e^{-C/T} \tag{5}$$

Thus, if A, B, and C can be determined from a best fit of the data to a curve of the form of either (5) or (3), then the magnitudes of A, B, and C determine the location of the recombination center. In our initial experiments, this latter method has been used with a least-squares error curve fitting method as described by Matthews and Warter[3] . This curve fitting technique was programmed on the IBM 1620 digital computer, and the results of the experiments are shown in Table I.

TABLE I

Sample	Total γ Dose(roentgens)	ΔE (ev)	$\mathcal{T}$po (μs)	$\mathcal{T}$no (μs)
1NA58-6	Pre Irradiation	$Ev^+.256$	231	4.86
"	5.10×10^4	$Ec^-.475$	54.3	___
"	1.02×10^5	$Ec^-.491$	42.1	___
"	2.03×10^5	$Ec^-.516$	37.7	___
"	3.06×10^5	$Ec^-.499$	26.9	___
1NA$\frac{1}{2}$5-10	Pre Irradiation	$Ev^+.249$	14.6	.04
"	5.10×10^4	$Ec^-.779$	20.5	___
"	1.02×10^5	$Ev^+.200$	15.5	.012
"	2.03×10^5	$Ev^+.027$	8.65	.122 nsec
"	3.066×10^5	$Ev^+.02$	8.65	.122 nsec

It appears that the energy level after irradiation is near the center of the gap and stays in this position (within experimental error) with increasing gamma dosage. However, near the surface the defect level seems to change position as the gamma dosage increases, with the energy level approaching the valence band edge. For this to occur, there must exist an increasing ratio of electron to hole capture cross section for this level in n-type material. This is true as can be seen by the large ratio of the $\mathcal{T}$po to $\mathcal{T}$no in Table I. There are two possible explanations for these phenomena. One is that the energy level at the surface stays in the same position with respect to the level in the bulk, with the increasing gamma irradiation causing a decrease in surface potential (the bands must bend upward

near the surface). If so, this would explain why there exists a minimum in the surface recombination velocity as the samples are irradiated. (see SDL report No. 2-588).

The other is that the gamma irradiation does change the position of the predominant energy level while the bands remain unchanged.

It is felt that once p-type samples are irradiated and the temperature dependence of the bulk and surface lifetimes obtained, more light will be shed on the possible explanation for the results presented here. Also, the data and the computer curve fit to the data indicate that an increased temperature range should be examined to investigate the possibility of multiple recombination centers, with further complexity of the mathematical models.

Thus, future work will include extended temperature ranges, with data taken on both n-and p-type samples. Investigations on surfaces prepared in different manners will be carried out during the next report period to examine the surface defects caused by gamma irradiation with respect to those present before exposure.

REFERENCES

1. J. Blakemore, Semiconductor Statistics, Pergamon Press, N. Y., N. Y., pp. 268-269, 1962.

2. W. Shockley and W. Read, Phys. Rev., 87, p. 835, Sept., 1952.

3. N. Matthews and P. Warter, Princeton University, Dept. of Electrical Engineering, Technical Report 7, April, 1964.

PROJECT NO. 588-2.   SURFACE STUDIES ON M. O. S. CAPACITORS

STAFF: R. J. MATTAUCH AND R. W. LADE

Semi-annual progress report #3 from the Semiconductor Device
Laboratory at North Carolina State University at Raleigh contains
a report on silicon surface state density changes induced by
gamma radiation (pp. 16-30). This section of report #4 is
devoted to the explanation of information gained on the above
mentioned topic from August, 1965 through March, 1966.

As one will recall, the method of Zaininger[1] is used to
determine surface state density as a function of surface potential
for the silicon. 50 p-type and 50 n-type devices have been
fabricated (see Figure 1). Point by point capacitance versus
bias voltage curves have been taken for one n-type (#14-45)
and one p-type (#36-44) device as a function of gamma radiation.
Table I gives irradiation data for these two devices. Figures
2 and 3 give curve families for these devices as a function of
gamma radiation. Figures 4 and 5 are plots of effective surface
state density versus surface potential for the above devices.

In order to take CV data on many devices in a short period
of time, we found it necessary to construct an automatic CV
plotter (see Figure 6). This plotter enables one to obtain a
capacitance-voltage plot in 20 seconds. Six devices, 3 p-type
and 3 n-type, were irradiated and subsequent CV curves were
taken. Figures 7 and 8 show CV curves for typical n-type and
p-type devices. The irradiation data for these two devices are
given in Table I. One will conclude on the basis of a cursory
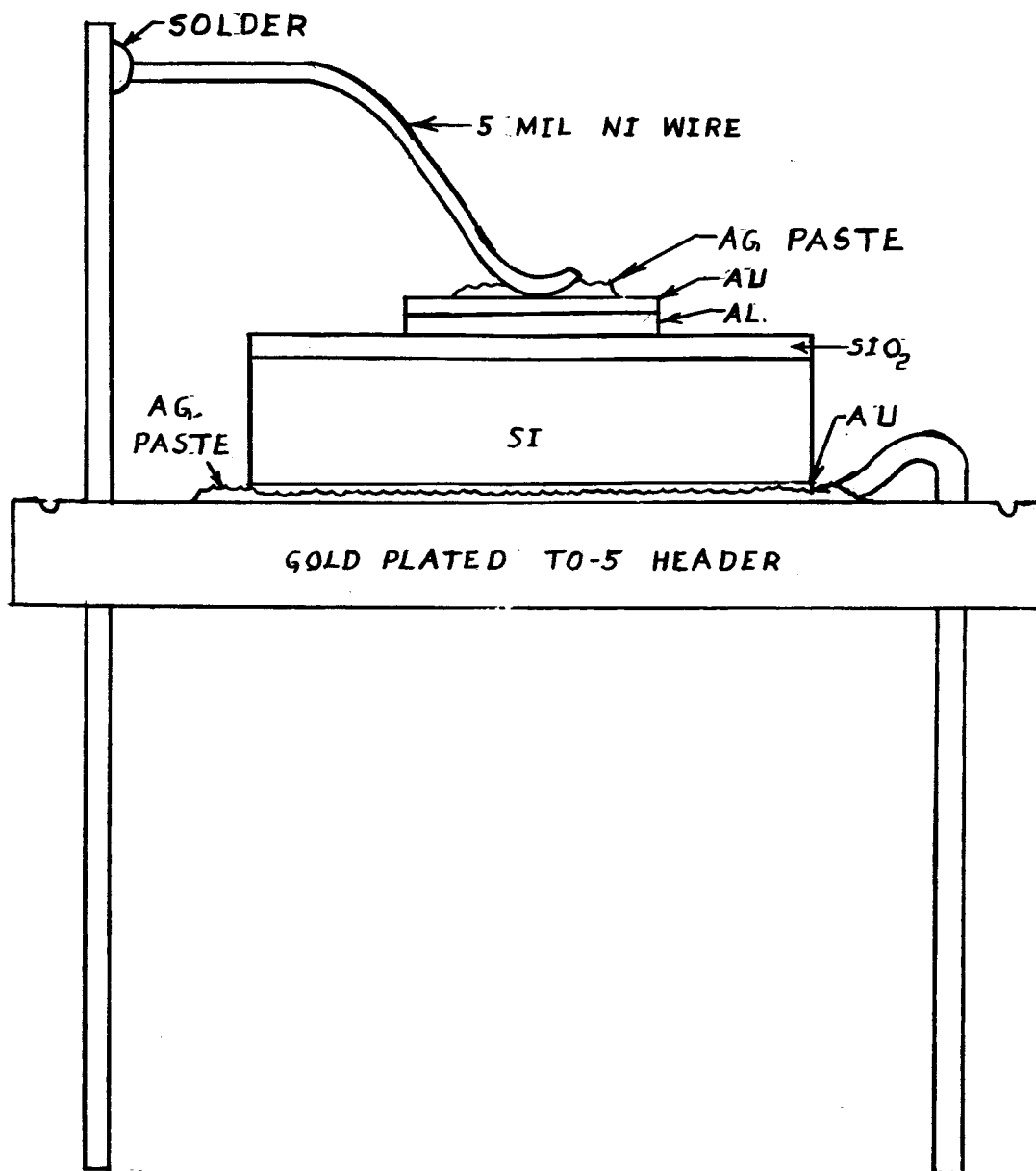
FIGURE 1: A TYPICAL DEVICE SHOWING
MOUNTING SCHEME ON
TO-5 HEADER

TABLE 1 — GAMMA RADIATION LOG   19

NUMBER	WAFER	DEVICE	DATE	TIME IN	TIME OUT	EXPOSURE
1	14	45	1/13/66	1624	1639	0.5×10^5 R.
2	"	"	1/16/66	1355	1410	" "
3	"	"	"	1610	1625	"
4	"	"	1/17/66	1420	1435	"
5	"	"	"	1605	1620	"
6	"	"	"	1955	2010	"
7	"	"	"	2135	2150	"
8	"	"	1/18/66	1005	1020	"
9	"	"	"	1210	1225	"
10	"	"	"	1940	2010	1.0×10^5 R
11	"	"	1/19/66	1040	1110	"
12	"	35	"	1805	1885	"
13	"	45	1/21/66	1230	1300	"
14	"	35	1/23/66	1420	1450	"
15	36 ①	44	1/25/66	1450	1510	0.5×10^5 R
16	" ②	"	1/27/66	1305	1325	"
17	" ③	"	"	1935	1950	"
18	" ④	"	1/28/66	1040	1110	1.0×10^5 R
19	" ⑤	"	"	1430	1500	"
20	" ⑥	"	1/29/66	1055	1125	"
21	" ⑦	"	"	1450	1520	"
22	" ⑧	"	1/30/66	1315	1345	"
23	" ⑨	"	1/31/66	1000	1030	"
24	" ⑩	"	"	1255	1355	2.0×10^5 R
25	" ⑪	"	"	1840	1940	"
26	" ⑫	"	2/1/66	0840	0940	"
27	" ⑬	"	"	1705	1905	4.0×10^5 R
28	" ⑭	"	2/2/66	0905	1105	"
29	" ⑮	"	"	2000	2200	"
30	" ⑯	"	2/3/66	1125	1525	8.0×10^5 R
31	" 17	"	"			
32	14–36	15,25,55 41,42,43	2/27/66	1315	1343	1.0×10^5 R
33	"	"	"	1425	1455	"
34	"	"	"	1525	1625	2.0×10^5 R
35	"	"	"	1700	1900	4.0×10^5 R
36	"	"	"	1935	2135	"
37	"	"	"	2230	0230	8.0×10^5 R
38	"	"	"	0300	0700	"
39	"	"	"	0730	1130	"
40	"					

FIGURE 2

DEVICE 14-15 : POINT BY POINT CAPACITANCE-BIAS CURVES
SHOWING SHIFT TO LEFT OF CURVES
WITH INCREASING ACCUMULATED GAMMA
IRRADIATION
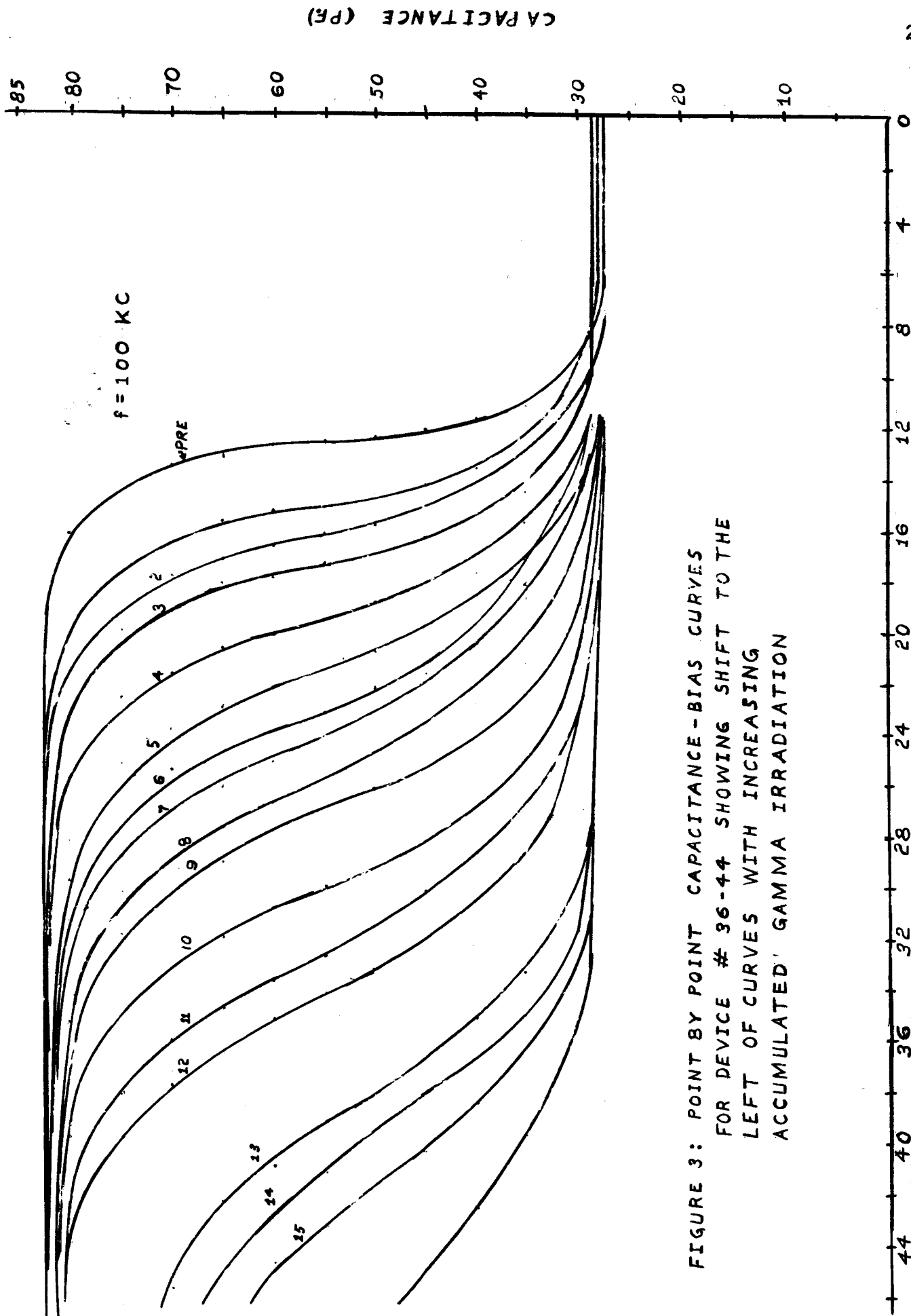
CAPACITANCE (PF)

NEGATIVE BIAS VOLTAGE
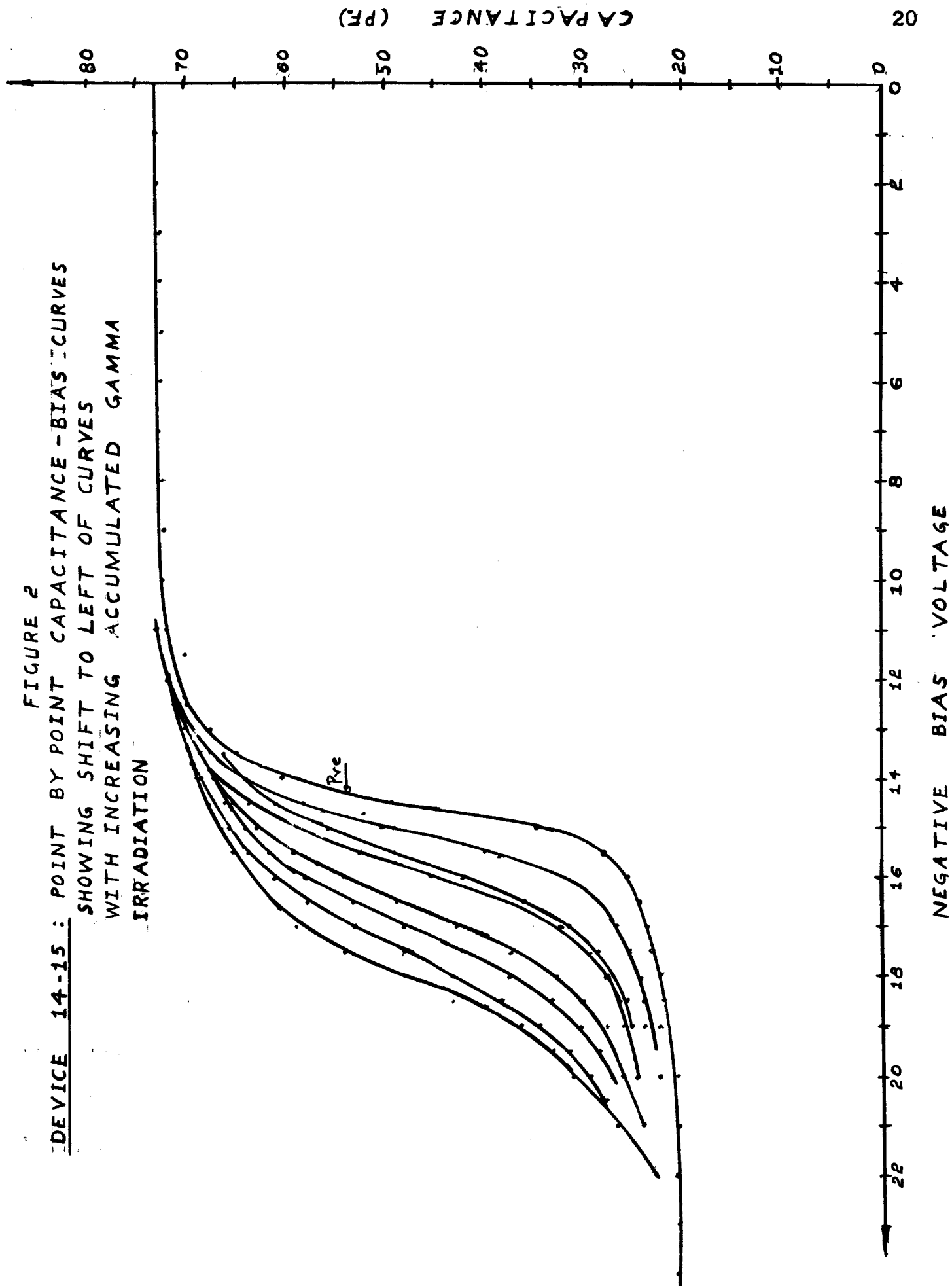
FIGURE 3: POINT BY POINT CAPACITANCE-BIAS CURVES
FOR DEVICE # 36-44 SHOWING SHIFT TO THE
LEFT OF CURVES WITH INCREASING
ACCUMULATED GAMMA IRRADIATION

NEGATIVE BIAS VOLTAGE
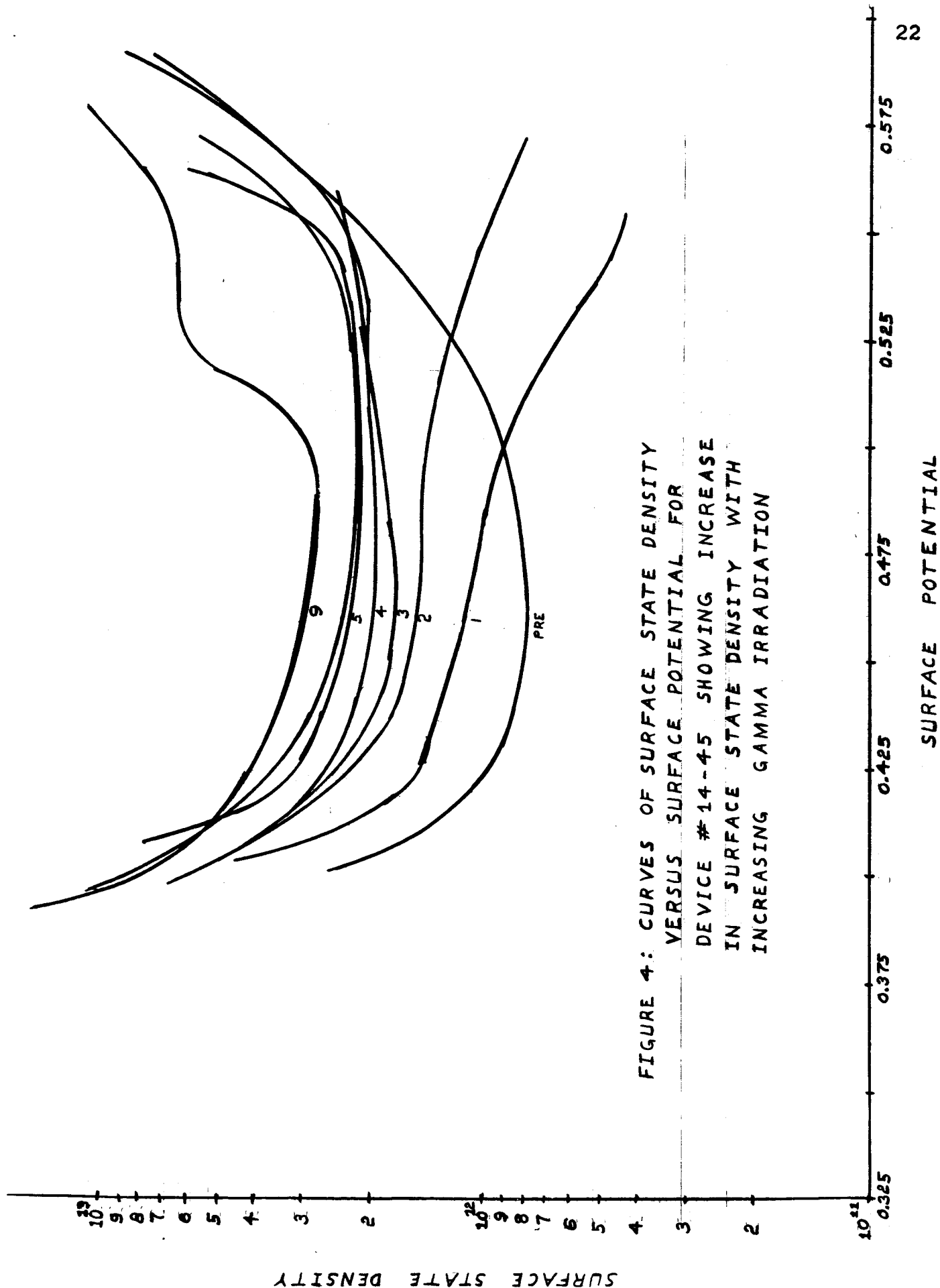
CAPACITANCE (PF)

f=100 KC

FIGURE 4: CURVES OF SURFACE STATE DENSITY
VERSUS SURFACE POTENTIAL FOR
DEVICE #14-45 SHOWING INCREASE
IN SURFACE STATE DENSITY WITH
INCREASING GAMMA IRRADIATION

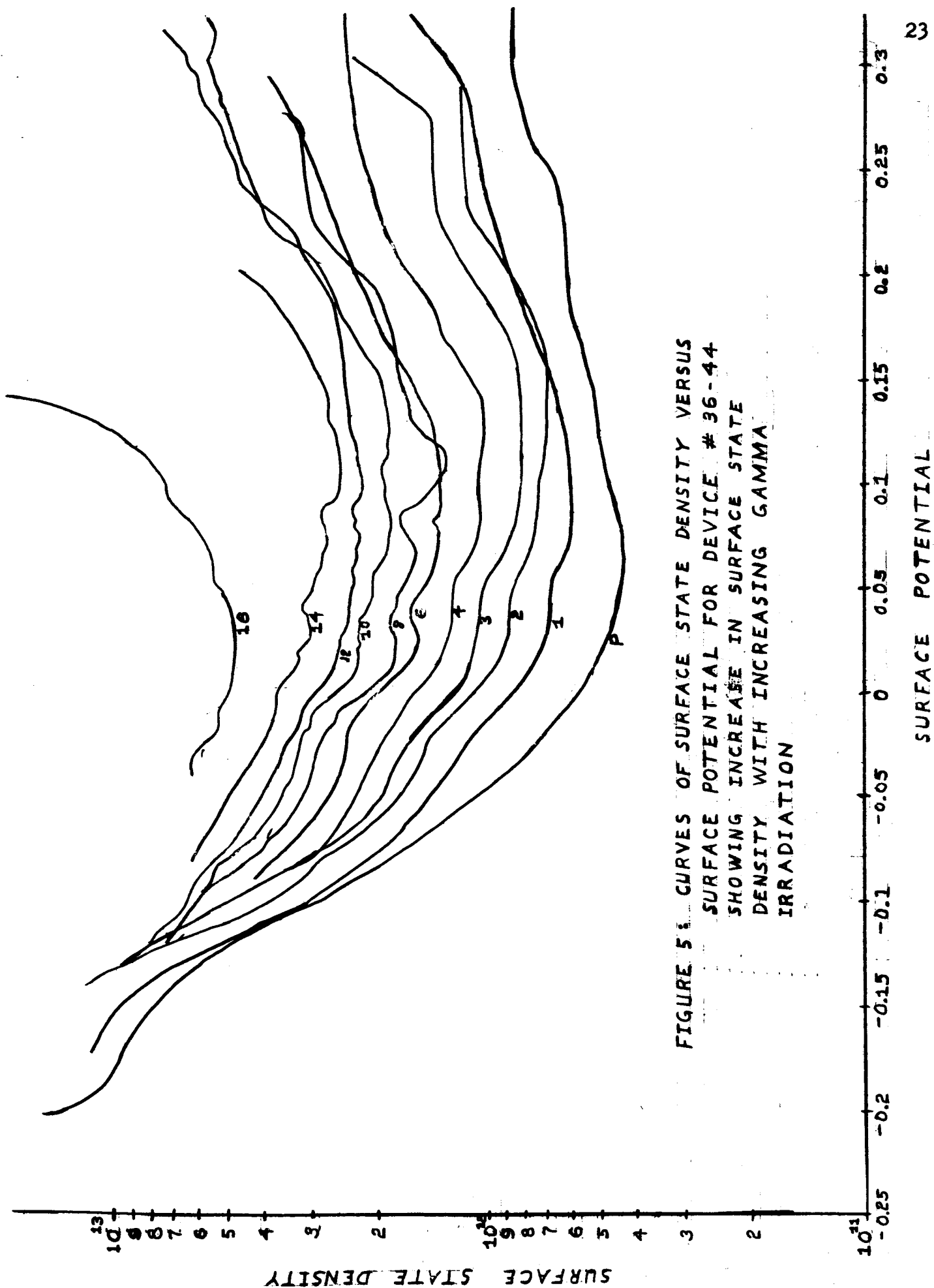SURFACE POTENTIAL

SURFACE STATE DENSITY

FIGURE 5: CURVES OF SURFACE STATE DENSITY VERSUS SURFACE POTENTIAL FOR DEVICE #36-44 SHOWING INCREASE IN SURFACE STATE DENSITY WITH INCREASING GAMMA IRRADIATION
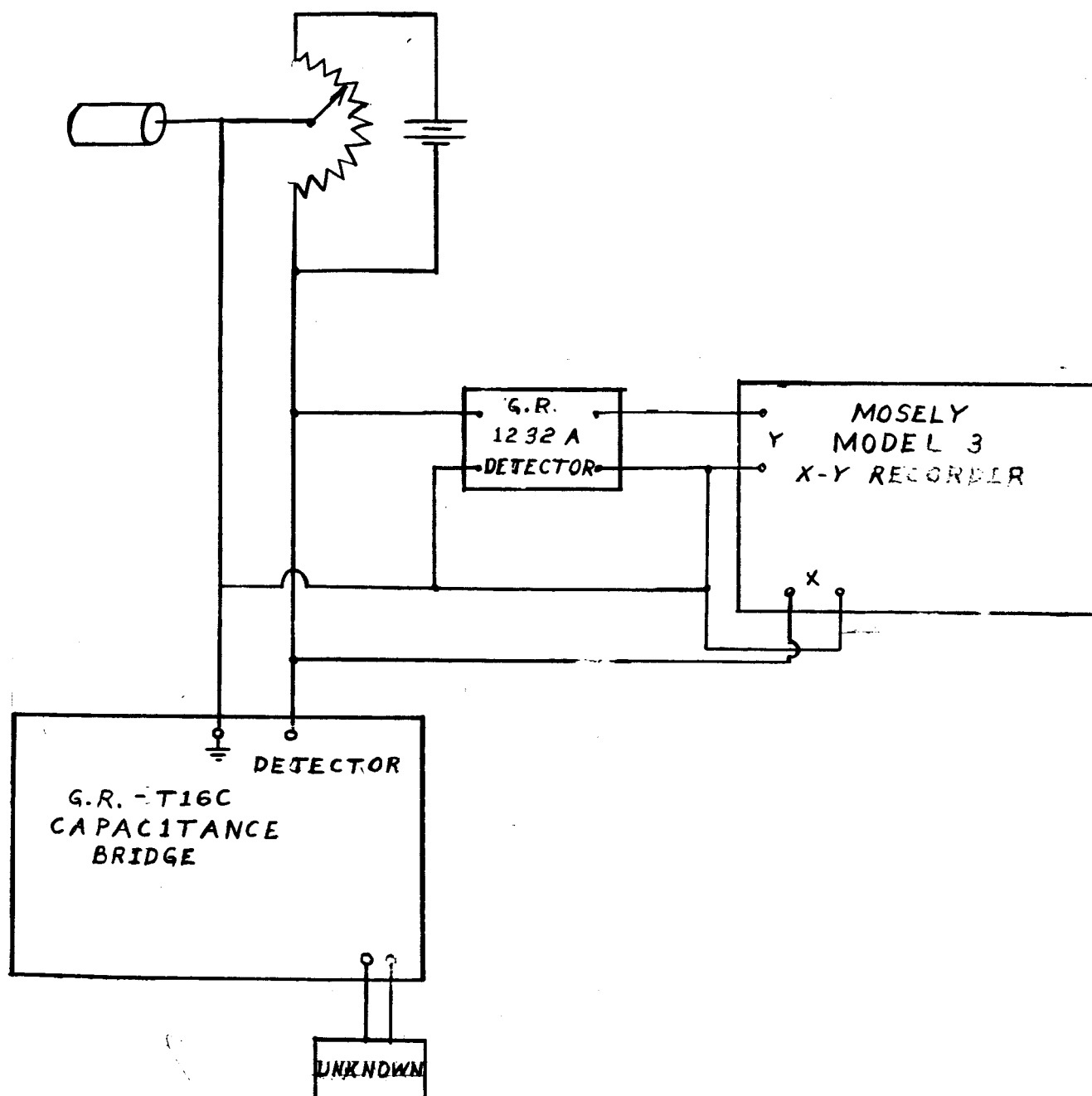
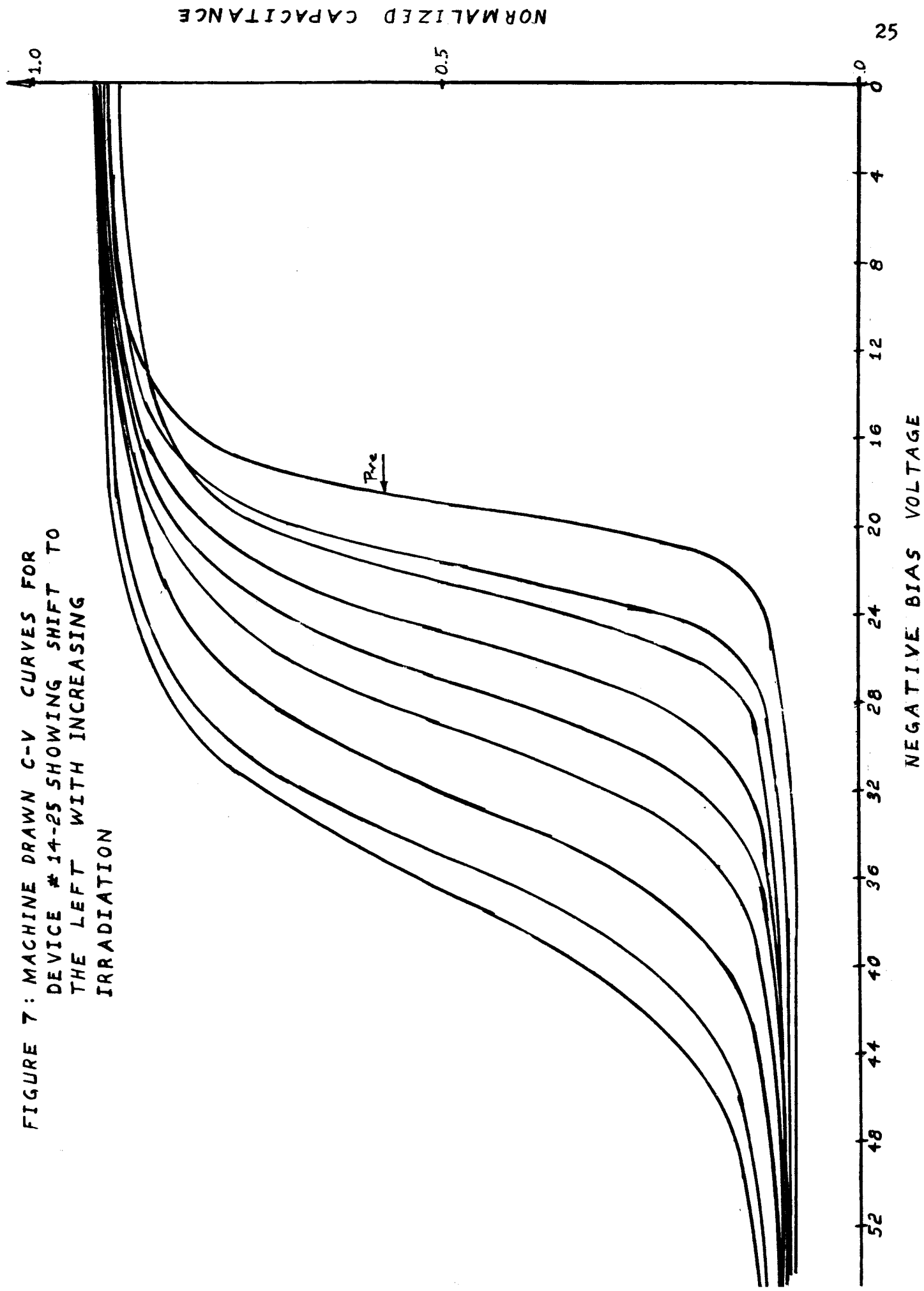SURFACE POTENTIAL

SURFACE STATE DENSITY

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FIGURE 6: BLOCK DIAGRAM OF C. VS V
RECORDING EQUIPMENT

FIGURE 7: MACHINE DRAWN C-V CURVES FOR DEVICE #14-25 SHOWING SHIFT TO THE LEFT WITH INCREASING IRRADIATION
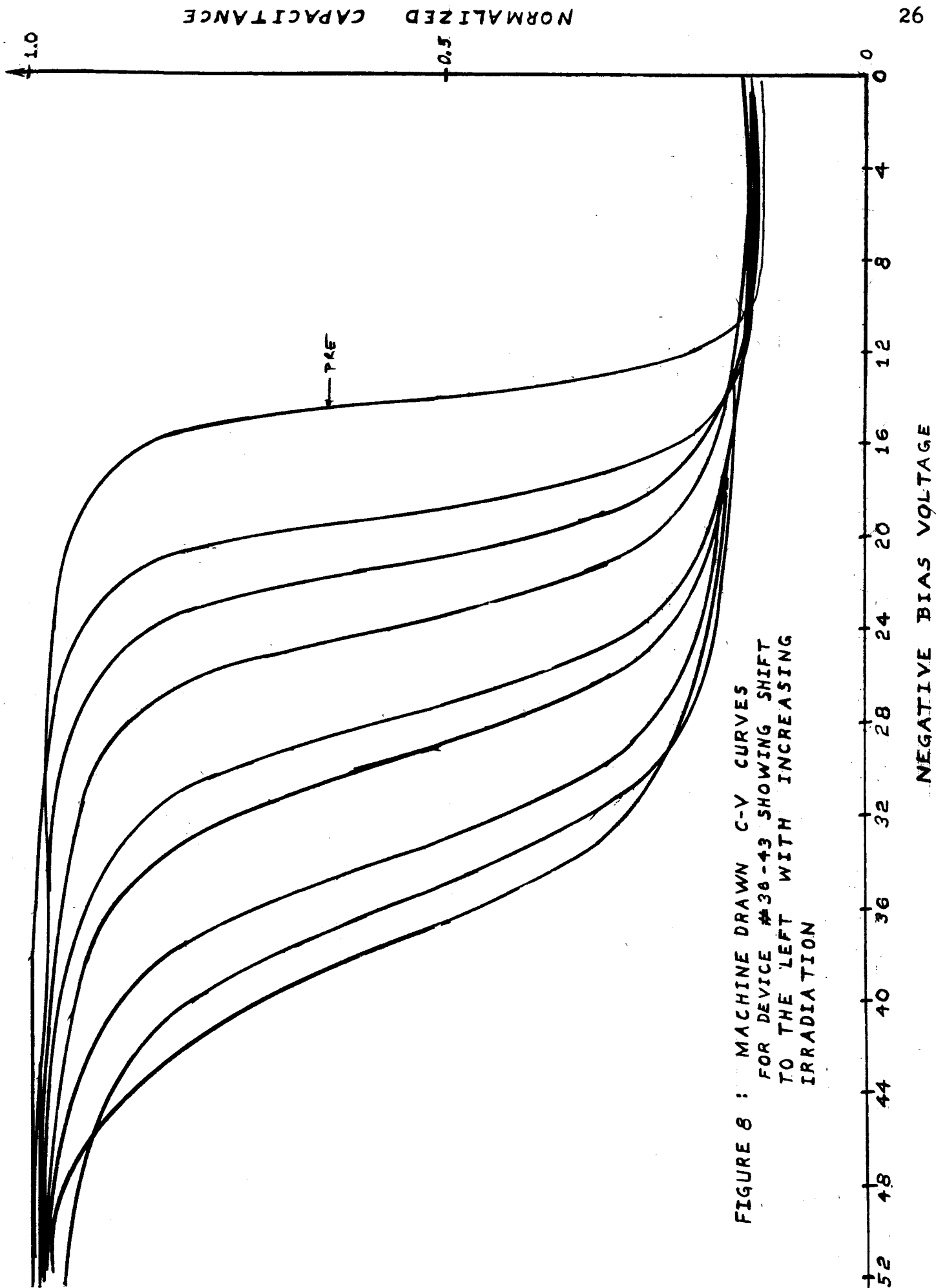
FIGURE 8 : MACHINE DRAWN C-V CURVES FOR DEVICE #36-43 SHOWING SHIFT TO THE LEFT WITH INCREASING IRRADIATION

NORMALIZED CAPACITANCE

NEGATIVE BIAS VOLTAGE

PRE

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examination of these curves and a comparison thereof with those of Figures 2 and 3 that the trends in horizontal displacement of the curves are the same. This was found to be true for all six devices used in the confirmation experiments.

The introduction of a positive charge density in the SiO_2 apparently causes the shift to the left in the CV curves. The questions which must now be asked are:

1. Are these charges distributed throughout the oxide and if so what is their distribution?

2. Are these charges mobile at room temperature and/or at elevated temperatures?

3. Can these charges be moved in the oxide by means of an applied bias at elevated temperatures and then be made immobile by room temperature quenching?

4. Are these charges perhaps due to alkali ions present in the oxide?

In order to find answers to these and other questions, one must devise a series of diagnostic experiments. These consist of subjecting devices to a variety of temperature and bias conditions for given periods of time and then using the automatic CV plotter to observe trends in curve movement.

Several p-type devices were subjected to the following experiments:

a. Heat to $75^{\circ}C$ with -5 volt bias applied to the gate.

b. Heat to $75^{\circ}C$ with +5 volt bias applied to the gate.

c. Heat to $75^{\circ}C$ with no bias applied.

These annealing experiments were carried out in an argon atmosphere. Table 2 exhibits various sequential bias and annealing steps taken with several devices. Capacitance versus bias plots along with probable charge diagrams are also shown in this table. The charge diagrams are constructed on the hypothesis that mobile alkali ions are present in the oxide. A possible explanation for each of these situations follows.

Case 1. Positive ions are supposed present in a layer of the oxide near the oxide-semiconductor interface. This causes the surface to be n-type with zero bias applied.

Case 2. Here it is supposed that the elevated temperature greatly increases the positive ion mobility. The applied bias causes a drift of positive ions toward the gate. Snow, et al.[2] show that this does tend to increase the capacitance seen for a given bias (i.e., shifts the CV curve toward zero bias).

Case 3. Once again the temperature increases the mobility of the positive ions and the bias causes them to drift toward the interface. In this case, some of the positive ions are able to get close enough to the silicon or just inside and cause the surface to be n-type and exhibit properties of an n-type substrate. Note that the left portion of the CV curve bends back up signifying that a copious supply of minority carriers (holes) are present near the n-type surface and thus are able to follow the applied signal.

TABLE 2

#	TIME	BIAS VOLTAGE	TEMP.	C-V CURVE	OXIDE CHARGE DISTRIBUTION
1	0	INITIAL			
2	4 hr	−5	75°C		
3	2 hr	+5	75°C		
4	1 hr	+5	75°C		
5	1 hr	−5	75°C		
6	1 hr	−5	75°C		
7	15 min	0	75°C		
8	1 hr.	−5	75°C		

Case 4. Same as Case 3.

Case 5. Assuming mobile ions due to the elevated temperature we see that the negative bias causes the ions to move toward the metal and remain there in a thin sheath. This causes less of an inversion layer at the surface.

Case 6. Same as Case 5.

Case 7. With no bias and a gradient of positive ions we see a diffusion of ions away from the gate thus inverting the surface even more.

Case 8. With a negative gate and mobile ions we are able to bring the electrons back into a thin sheath at the gate.

Experiments attempting to explain pre- and post-radiation charge densities in the SiO_2 will continue through the next report period.

REFERENCES

1. K. H. Zaininger and G. Warfield, "Limitations of the MOS capacitance method for the determination of semiconductor surface properties," IEEE Trans. on Electron Devices, Vol. ED-12, pp. 179-193, April, 1965.

2. E. Snow, A. S. Grove, B. E. Deal, and C. T. Sah, "Ion transport phenomena in insulating films," J. Appl. Phys., Vol. 36, pp. 1664-73, May, 1965.

PROJECT NO. 588-3.   MEASUREMENT OF SURFACE RECOMBINATION VELOCITY
AS A FUNCTION OF SURFACE POTENTIAL

STAFF: F. J. MORRIS AND R. W. LADE

The objective of this project is to determine experimentally
the effects of surface potential on the surface recombination
velocity of an oxide-silicon surface and its variation with
gamma radiation.

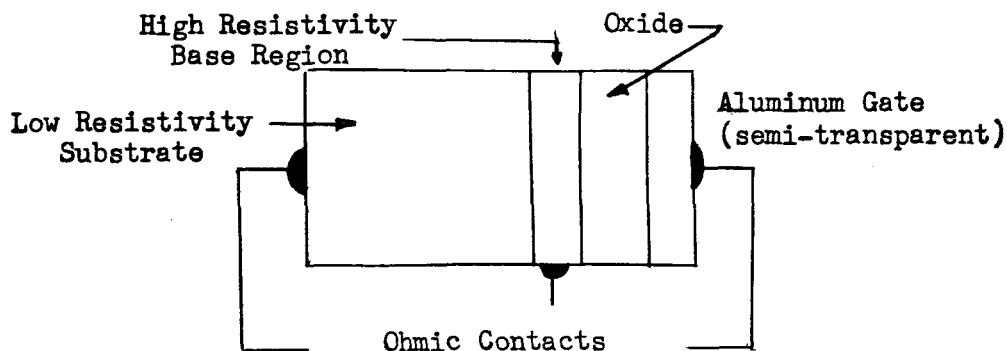The device to be used is shown in Figure 1.

Figure 1.   Proposed device for measuring surface recombination
velocity.

The base region is a high resistivity region in order that
the silicon-oxide interface will determine the v-i character-
istics of the device. Several attempts have been made to diffuse
a high resistivity region into a low resistivity substrate. The
first attempts were made by chemically polishing 70 ohm cm

N-type Merck silicon and evaporating a thin coat of aluminum onto the silicon. The samples were placed in a diffusion furnace for 2.5 hours at 1250°C. The diffused region was approximately 0.7 mils deep. The diffused front was very irregular as determined by staining the junction. The v-i characteristics were very poor. The devices exhibited no saturation current in the reverse direction and had a nominal reverse breakdown voltage of 2 volts.

Samples of 2 ohm cm N-type Monsanto silicon were chemically polished and taken to the Research Triangle Institute where they were diffused at 1200°C for 15 minutes using diborane gas as the dopant. The oxide was then removed from the samples and the samples were diffused at 1300°C for six hours. Oxygen bubbled through water at 25°C flowed through furnace tube at 2 liters per minute with no dopant present. The samples were then sliced and stained and no improvement was found. Some regions on the surface were P-type while others were N-type as indicated in the photographs and borne out by thermal probe measurements. This apparent masking of part of the silicon was probably due to an oxide formed during the first step of the two step diffusion. Oxygen was present in the carrier gas and apparently the oxide did not grow evenly across the surface. Due to the low concentration of the dopant gas (in order to obtain a high resistivity region) the oxide did not act as a source of the dopant.

Other samples have been carried through this two-step diffusion process with the only difference being in the first

step. Oxygen was removed from the carrier gas and the deposition time increased. The final results on these samples have not been obtained yet.

Some epitaxial P-N junctions and N-P junctions have been purchased with the desired characteristics. The epitaxial layer resistivity is nominally 10 ohm cm and the substate is .02 ohm cm. Work will be carried out on both diffused and epitaxial junctions.

Some work has been carried out to determine the relationship between the amount of aluminum evaporated on a glass slide and its electrical conductance and light transmissivity. This information will be used in the gate design.

A technique was developed to stain p-n junctions very similar to that in the literature.

Work is presently being carried out to develop the technique for photoetching.

PROJECT NO. 588-4. DEEP LYING CENTERS IN GERMANIUM

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V. I. Stafeev in a series of papers (Soviet Phys. Tech. Phys., 3, p. 1502, 1958, Soviet Phys.-Solid State, 1, p. 763, 1959) has proposed that the variation of the diffusion length, and therefore, lifetime, in a semiconductor, could provide the basis for new semiconductor devices and the explanation of phenomena noted by Tyler (Phy. Rev., 96, p. 226, 1954) and Lebedev, Stafeev, Luchkevich (Sov. Phy. - Tech. Phy., 1, p. 2071, 1956) in iron- and gold-doped germanium. In particular if the lifetime of the excess carriers should increase with increased carrier injection, then a negative resistance region should be exhibited in the forward VI characteristic of a long base (base much greater than diffusion length) diode.

It was decided to look further into this lifetime variation effect on diodes, both from the theoretical and experimental point of view. As Stafeev himself noted, his analysis of the charge transport was approximate. Some of his assumptions are of a first order nature to gain a look into a new principle. Thus, much work is left in the analytic domain for long base diodes operating under conditions sufficient to cause the lifetime to vary. The technique of Lade (Ph.D. thesis, Carnegie Tech. 1962) lends itself well to this problem and eliminates the need of Stafeev's unity injection efficiency assumption. The problem has been solved for a constant lifetime with fewer assumptions for heavy injections. The case for variable lifetime and

mobility lead to a nonlinear differential equation which will be solved completely and with a minimal number of assumptions by numerical techniques.

If different dopants can be found to produce the necessary lifetime variations, then the obvious problem is posed - what parameters (trap level, capture cross section, temperature, doping level) will yield the greatest negative resistance? The lifetime under injection was analyzed by the model proposed by Schockly, Read, Hall (Phy. Rev., 87, p. 835, 1952), henceforth called the S-R-H model. The obvious technique of taking the partial derivatives with respect to the variables and obtaining the extremum was not used for two reasons. One, the equations are transcendental and there is no guarantee that the values of the parameters would be physically realizible. Two, not a very complete picture would be gained from knowledge only of the extrema. Thus, a parameter variation study was run on the IBM 1620 to discover the best lifetime variations. This study has been completed. The dopants which provide the recombination paths are multivalent. This means that the S-R-H single trap model was inapplicable. Whereas, for a narrow range of conditions, if all the conditions are being varied then a single model does not give the true story.

At this stage the theory of multivalent recombination and trapping is being studied in order to determine how they can be used to shape the lifetime variation.

Another aspect of Stafeev's work that needs some attention is to experimentally confirm the fact that lifetime increase under increased injection will result in a negative resistance. In none of his work is any mention made of an experimental determination of lifetime as a function of excess carrier density and using this to predict the V-I curves.

Work is just getting underway to start the experimental procedure and prepare samples for measurement.